A Sociotechnical Approach to the Museum Congestion Management Problem

Athina Thanou, Eirini Eleni Tsiropoulou, and Symeon Papavassiliou

***Abstract*— In this article, a sociotechnical consideration of the congestion management problem in museums is presented, by treating museums as dynamic social systems, where the momentum of the experience is controlled by visitors themselves. Visitors are considered as prospect-theoretic utility maximizers, whose behavioral risk attitudes affect not only their personal decisions and experiences but also those of others, thus creating an interdependent social system. To address the congestion problem within such a probabilistic and uncertain environment, pricing is introduced as an effective mechanism to drive visitor actions in efficient operation points, preserving museum operation stability. The corresponding problem of determining the time invested by each visitor at museum exhibits toward optimizing their obtained experience, as expressed via properly designed prospect-theoretic utility functions with pricing, is formulated and treated as a noncooperative game. The theory of S-modular games is adopted to prove existence and convergence to Nash equilibrium. Based on this framework, we study and analyze the validity and effectiveness of pricing as a tool to manage congestion in museums.**

***Index Terms*— Museum congestion management, pricing, Prospect Theory, quality of experience (QoE), S-modular games, sociotechnical systems.**

I. Introduction

CYBER physical social systems (CPSS) [1] present evolving and dynamic environments, exhibiting constraints and interdependencies among the involved subjects. Consequently, behavioral characteristics of subjects become of paramount importance in studying the operation, efficiency, and effectiveness of CPSSs. As a result, in recent literature, various efforts have been devoted to integrating risk preferences in the optimization process and evaluation of various social and technical systems, such as cultural heritage spaces, finance, and industrial organizations [2]–[5].

In this article, the focus is placed on museums, whereas opposed to other social environments, the momentum of the experience is primarily controlled by visitors themselves. Understanding the interdependencies among visitors is crucial in order to design computationally efficient decision-making approaches that will positively influence visitor touring and museum congestion. Congestion (or overcrowding) may result in uncomfortable situations for visitors, such as queuing, noise, and challenges when viewing popular exhibits, which, in turn, negatively affects visitor quality of experience (QoE) [6].

A. Challenges and Article Contribution

Considering the aforementioned challenges, in [2], a realistic approach to the museum congestion management problem was introduced, and the impact of visitor behavioral factors was analyzed and assessed. By exploiting Prospect Theory [7], a distributed approach was devised in order to determine visitor optimal investment time at exhibits while maximizing their perceived satisfaction. However, as visitors want to improve their own QoE, they engage in a form of competition with respect to gaining access to exhibits. Such behavior, in cases of overcrowding, can lead an exhibit to a virtual collapse, in the sense that none of the visitors gain any satisfaction, a phenomenon described in the literature as Tragedy of the Commons [8].

Exhibits, especially popular ones, should, therefore, be treated as potentially congestible resources, which are both nonexcludable (i.e., any visitor may access them) and subtractable (i.e., the observation by one visitor reduces the ability of being observed by another). This consideration gives rise to the concept of resource fragility, which is associated with resource collapse probability due to overexploitation. This, in turn, motivated us to introduce pricing as a means to further guide visitor behavior and decisions in order to achieve more efficient operation for the museum and more positive experiences for visitors.

In this article, we integrate the concepts of visitor time investment at exhibits, resource fragility, and pricing under a common umbrella, by utilizing the principles of Prospect Theory that considers visitor subjectivity in decision making, thus providing a sociotechnical perspective. Our article aims to shed some light on the impact of visiting pricing mechanisms on both visitor QoE and the fragility of exhibits. We argue that the adoption of pricing constitutes a valid measure against overcrowding. It drives visitors to take decisions that prevent them from overexploiting exhibits, thus reducing the likelihood of exhibit "failure" and preserving museum operation stability. The rest of the article is structured as follows. In Section II, the system model is presented, while in

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Section III, the formulation of the corresponding optimization problem and its solution based on S-modular game theory are described. Section IV contains the evaluation of the proposed approach, while Section V concludes the article.

II. System Model

A. Assumptions and Pricing Motivation

Visitor decisions about which exhibits to view and how much time to spend at each one constitute decisions that entail risk. The outcome of visiting a popular exhibit is neither guaranteed nor always positive. Following the reasoning introduced in [2], artworks are classified into two main categories: safe and common pool resource (CPR) exhibits. Safe exhibits are less well known and thus less congested, which results in satisfaction for visitors, when time is invested in observing them. By contrast, CPR exhibits are works that are famous and potentially overcrowded. CPR is a resource that may significantly benefit a group of people but provides diminished benefits to everyone if each individual pursues their own self-interest. A CPR may experience "failure" due to overexploitation, with a probability that increases as visitor's total time invested at CPR increases.

To prevent overexploitation of CPR exhibits, we adopt a pricing mechanism where visitors are charged according to how much time they invest at CPR exhibits [6], [9]. In several computational, technical, and physical social systems, pricing has been considered, as a flexible and effective mechanism, which drives user decisions and actions toward more efficient museum operation, from a social welfare point of view [10]–[13]. A survey conducted via questionnaire in the British Museum revealed that only 1% of respondents visited the museum because it was free, while more than 15% claimed that congestion was what they disliked the most in relation to their visiting experience, and were willing to pay higher charges so as to obtain improved QoE [6].

B. Utility Function Modeling With Pricing

In our model, we consider N visitors, where $\aleph = \{1, 2, \ldots, N\}$ denotes their set, and each visitor has an available actual visiting time $t_i^{\max}$. Part of the time, t_i, is invested in observing CPR exhibits and the remaining, ${t_i}^{\max} - t_i$, in visiting safe exhibits. For simplicity and without loss of generality, in the following analysis, we consider the normalized visiting time set $T_i = [0, 1]$, where the upper bound $t_i^{\max}$ is assumed to be equal to one for all visitors. Visitor perceived actual utility gained from safe exhibits is a linear function with respect to visitor invested time, ${t_i}^{\max} - t_i$, at safe exhibits and is given as follows [2]:

$$z_i^{\mathrm{SAFE}}(t_i) = w_i \cdot \left(t_i^{\max} - t_i\right) \tag{1}$$

where w_i expresses the overall importance of safe exhibits for visitor i and is defined via the combination of safe exhibit historical importance $e_w \in [0, 1]$ and visitor subjective interest $I_i \in [0, 1]$ in the specific safe exhibits, i.e., $w_i = e_w \cdot I_i$.

Regarding visitor perceived actual utility gained from CPR exhibits, we investigate the impact of an exponential charge as a means to avoid exhibit "failure" and resulting visitor dissatisfaction. Therefore, if a visitor i invests t_i time at CPR exhibits, they are charged proportionally to their invested time, i.e., $c \cdot {t_i}^y$. The parameters c, y are configurable and positive, with $y \geq 1$ and $c \in [0, 1]$, and they are elaborated on later in the article. Consequently, visitor's i perceived actual utility from CPR exhibits is given as

$$z_i^{\mathrm{CPR}}(t_i) = {w_i}^c \cdot \frac{t_i}{t_T} \cdot F(t_T) - c \cdot t_i^y. \tag{2}$$

The first part of (2) reveals that visitor perceived actual utility at CPR exhibits depends not only on time invested but also on total invested time by all visitors, $t_T = \sum_{i=1}^{N} t_i$ (which implicitly reflects congestion). The production function $F(t_T)$ signifies the return for visitors from CPR exhibits and depends on total invested time, t_T, at CPR exhibits. Following from the existing literature [2], [14], $F(t_T)$ is assumed to be concave with $F(0) = 0, F'(0) > w_i$ and $F'(N \cdot t_i^{\max}) < 0$. The parameter $w_i^c \in [0, 1]$ signifies the importance of CPR exhibits for visitor i, while for simplicity and without loss of generality, we assume that $w_i^c = 1$ due to the importance of those exhibits. To simplify the above-mentioned equation, we define the rate of return function $r(t_T) = (F(t_T)/t_T)$, which is nonincreasing, monotonic, concave, twice continuously differentiable with respect to the normalized total investment time $t_T, t_T \in [0, 1]$ and $r(t_T) > 1$. Therefore, visitor i perceived actual utility from CPR exhibits is obtained as

$$z_i^{\mathrm{CPR}}(t_i) = t_i \cdot r(t_T) - c \cdot t_i^y. \tag{3}$$

Combining (1) and (3), visitor total perceived actual utility becomes

$$z_i(t_i) = w_i \cdot \left(t_i^{\max} - t_i\right) + t_i \cdot r(t_T) - c \cdot t_i^y. \tag{4}$$

C. Prospect Theoretic Framework Under Pricing

The key to improving visitor museum experience is to understand unknown visitor behavior. When visitors need to make risky choices, they tend to exhibit risk-seeking or risk-averse behavior according to their personal characteristics. A visitor's decision about how much time to invest at a CPR exhibit involves risk because a CPR may be congested, in which case the visitor may gain no satisfaction from it. We exploit the principles of Prospect Theory to properly formulate visitor QoE while taking visitor risk-aware behavioral characteristics into account. The prospect-theoretic utility function of a visitor i is given as

$$u_i(z_i) = \begin{cases} (z_i - z_0)^{a_i}, & z_i \geq z_0 \\ -k_i(z_0 - z_i)^{a_i}, & z_i < z_0 \end{cases} \tag{5}$$

where z_i is the visitor's perceived actual utility as defined in (4) and z_0 denotes the reference point of the visitor's prospect-theoretic utility. People typically tend to evaluate gains and losses not as absolute values but with respect to a reference point. In our work, the reference point for a visitor i is defined as the perceived actual utility that they get if all their available time, $t_i^{\max}$, is invested at safe exhibits, and it is given as follows:

$$z_0 = w_i \cdot t_i^{\max}. \tag{6}$$

The parameter $a_i \in (0, 1]$ is the sensitivity parameter and expresses the sensitivity of a visitor toward gains and losses. Smaller values of a_i indicate a higher increase in prospect utility for small values of actual utility, as well as a greater decrease in prospect utility for values close to the reference point z_0. In addition, parameter $k_i \in [0, \infty)$ signifies the importance someone places on gains and losses. Specifically, if $k_i > 1$, then a visitor is loss averse and weights losses more than gains, whereas when $0 \le k_i \le 1$, the visitor is gain-seeking and weights gains more than losses. Combining (4)–(6), the prospect-theoretic utility function for a visitor i can be rewritten as

$$u_i(z_i) = \begin{cases} t_i^{a_i} \cdot \left(r(t_T) - w_i - c \cdot t_i^{y-1}\right)^{a_i}, & z_i \ge z_0 \\ -k_i \cdot t_i^{a_i} \cdot \left(c \cdot t_i^{y-1} + w_i\right)^{a_i}, & z_i < z_0. \end{cases} \tag{7}$$

In the case of CPR "failure" (i.e., $z_i < z_0$), visitor i gains satisfaction only from observing safe exhibits. However, even if the visitor gains no utility from CPR exhibits, they still have to pay for the cost of visiting them. The probability of CPR "failure" is denoted by $p(t_T)$ and according to the concept of the Tragedy of the Commons [2], [8], it is assumed to be convex, strictly increasing, and twice continuously differentiable with respect to $t_T \in [0, 1]$ with $p(t_T) = 1, \forall t_T \ge 1$. For demonstration purposes and in line with the aforementioned assumptions, we select $p(t_T) = t_T$ (i.e., linear function).

Accordingly, based on (7) and taking into account the uncertainty introduced by the probability of "failure," the expected prospect-theoretic utility of visitor i is given by

$$\mathbb{E}(u_i) = t_i^{a_i} \cdot f(t_i) \tag{8}$$

where $f(t_i) \triangleq \overline{r}(t_T) \cdot (1 - p(t_T)) - k_i \cdot p(t_T) \cdot (c \cdot t_i^{y-1} + w_i)^{a_i}$ is the effective rate of return of CPR exhibits for the visitor i and $\overline{r}(t_T) = (r(t_T) - w_i - c \cdot t_i^{y-1})^{a_i}$. The function $\overline{r}(t_T)$ is decreasing, concave, and positive with respect to visitor time investment. The more time visitors spend, the more congested the museum becomes and the more visitor expected prospect-theoretic utility decreases. Analyzing the properties of function $\overline{r}(t_T)$ and after proper mathematical derivations, we conclude with the constraint (assuming $c \neq 0$)

$$t_i < \sqrt[y-1]{\frac{1 - w_i}{c}}, \quad w_i \in [0, 1]. \tag{9}$$

III. Problem Formulation and Optimization

A. Formulation

Every visitor wishes to maximize their QoE without considering the impact of their decisions (i.e., investment time at exhibits) on others. The goal of this article is to find the optimal invested time at CPR exhibits for each visitor in order to maximize their expected prospect-theoretic utility, under the considered general pricing framework. It is noted that pricing as a means of controlling exhibit fragility under probabilistic uncertainty has not been investigated in the context of Prospect Theory modeling in relevant works (see [2]). The contribution of our work is to fill this research gap and demonstrate that a pricing mechanism reduces CPR exhibit "failure" probability. It is achieved via a mathematical formulation of the corresponding problem based on the theory of S-modular Games [15], [16], as detailed in the following.

Based on (8), the problem is formulated as a maximization problem of the expected prospect-theoretic utility of each visitor i, while considering visiting time limitations, $t_i \in T_i = [0, 1]$ as well as the constraint (9):

$$\max_{t_i \in T_i} \mathbb{E}(u_i) = t_i^{a_i} f_i(t_i). \tag{10}$$

B. Solution

The above-mentioned maximization problem can be considered as a noncooperative game among visitors who act as rational players making optimal decisions about themselves in a selfish and distributed manner. Let $G = [\aleph, T_i, \mathbb{E}(u_i)]$ denote the noncooperative game among N visitors where $T_i = [0, 1], \forall i \in \aleph$ indicates the strategy space of each visitor i, and $\mathbb{E}(u_i)$ indicates the expected prospect-theoretic utility each visitor i gains from game G. As mentioned before, the class of S-modular Games is adopted to treat this problem. In particular, submodular games are characterized by strategic substitutes, which means that an increase in the actions of one player leads other users to decrease their actions accordingly. Submodular games are well aligned with the problem of optimizing investment and pricing in Fragile CPR problems since user strategies are shaped with respect to the probability of CPR fragility and the visiting cost due to pricing. Toward solving this noncooperative game, the Nash equilibrium concept is adopted.

We will first prove that the game is submodular and thus that there exists a Nash equilibrium.

Definition 1 (Submodular Function): If the function $\mathbb{E}(u_i)$ has derivatives of all orders, then $\mathbb{E}(u_i)$ is a submodular function, if and only if the following holds true $\forall i \in \aleph$:

$$\frac{\partial^2 \mathbb{E}(u_i)}{\partial t_i \partial t_j} \le 0. \tag{11}$$

Definition 2 (Submodular Game): A strategic game G is said to be submodular if:

1) $\forall i \in \aleph, T_i$ is a compact subset of the Euclidean space;
2) the function $\mathbb{E}(u_i)$ is sub-modular in t_i for each fixed $t_j, \forall j \in \aleph$.

Theorem 1 (Existence of Pure Nash Equilibrium): The noncooperative game G with pricing is a submodular game, thus it has at least one pure Nash equilibrium (PNE).

Proof: Initially, it is evident that the set $T_i = [0, 1]$ is a compact subset of the Euclidean space. Then, we calculate: $(\partial^2 \mathbb{E}(u_i)/\partial t_i \partial t_j) = t_i^{a_i - 1} h(t_i)$, where $h(t_i) = -a_i \overline{r}(t_T) - k_i a_i (c t_i^{y-1} + w_i^{a_i}) + t_i(1 - t_T)(\partial^2 \overline{r}(t_T)/\partial t_i \partial t_j) - k_i a_i c(y - 1) t_i^{y-1} (c t_i^{y-1} + w_i)^{a_i - 1} + (a_i(1 - t_T) - t_i)(\partial \overline{r}(t_T)/\partial t_j) - t_i(\partial \overline{r}(t_T)/\partial t_i)$. Given that the function $\overline{r}(t_T)$ is decreasing, concave, and positive, we conclude that the first four terms of $h(t_i)$ are negative. We set $\phi(t_T) = (a_i(1 - t_T) - t_i)(\partial \overline{r}(t_T)/\partial t_j) - t_i(\partial \overline{r}(t_T)/\partial t_i)$. By applying the intermediate value theorem, we have: $\phi(t_T = 0) = a_i(\partial \overline{r}(t_T)/\partial t_j) < 0$ and $\phi(t_T = 1) = -t_i(\partial \overline{r}(t_T)/\partial t_j) - t_i(\partial \overline{r}(t_T)/\partial t_i) > 0$. Thus, there exists at least one value $\mu \in T_i = [0, 1], \forall i \in \aleph$,

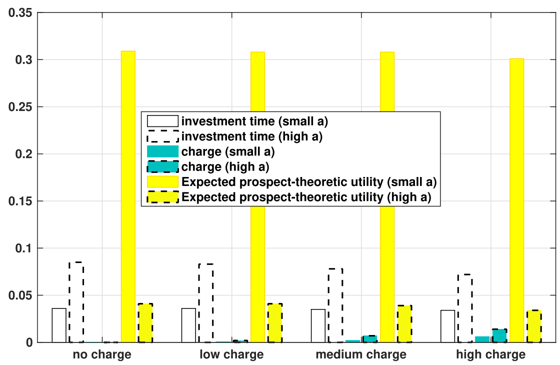


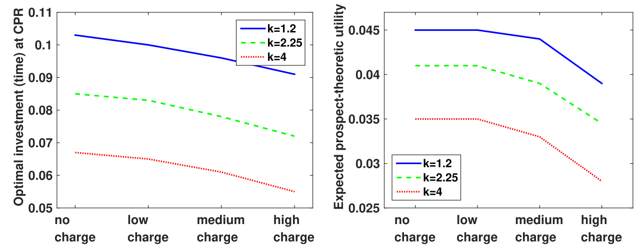
Fig. 1. Impact of different pricing alternatives on visitor time investment and expected prospect-theoretic utility for two different sensitivity parameters a.

such that $h(\mu) = 0$. Given that $\phi(t_T = 0) < 0$, then $h(t_T) < 0, \forall t_i \in (0, \mu)$. Based on the above analysis and (9) (assuming $c \neq 0$), we conclude that the game G is submodular $t_i \in (0, \lambda)$, where $\lambda = \min\{\mu, \sqrt[y-1]{((1 - w_i)/c)}\}$, $w_i \in [0, 1]$, thus there exists at least one PNE $t_i^* \in (0, \lambda), \forall i \in \aleph$. □

IV. Evaluation and Results

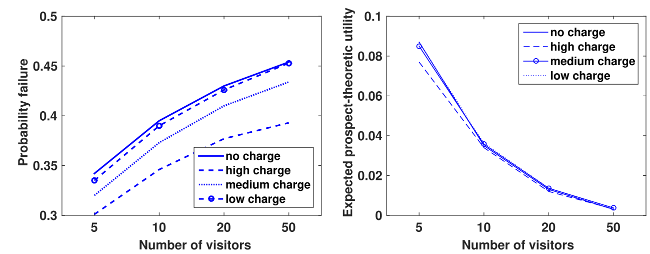
In this section, we present a series of numerical results to evaluate the impact of pricing on both visitor experience (expressed via the expected prospect-theoretic utility) and museum operation stability (in terms of CPR "failure" probability) under different visitor behavioral parameters scenarios. For purposes of comparison, three different pricing alternatives are evaluated, referring to different configurations of the parameter y of the pricing function, $c \cdot {t_i}^y$, as follows: 1) a low charge: minimal pricing, reflected by a higher value of $y = 1.8$; 2) a medium charge: average pricing, reflected by $y = 1.3$; and 3) a high charge: aggressive pricing, reflected by a lower value of $y = 1$. In all the above cases, parameter c is assumed equal to 0.2. Also, the "no charge" option refers to a baseline scenario where only prospect-theory is applied without pricing [i.e., $c = 0$ in (2)]. Similar to [2] and for demonstration only purposes, we have considered the following production function $F(t_T) = -2t_T^2 + 3t_T$ for all cases.

Fig. 1 illustrates how different pricing alternatives influence visitor time investment at CPR exhibits and visitor expected prospect-theoretic utility. Two different scenarios have been considered with respect to the sensitivity parameter (low where $a = 0.2$ and high where $a = 0.8$). It can be observed that as the charging becomes more aggressive (i.e., lower value of y), both visitor time investment and expected prospect-theoretic utility decrease. Based on the framework operation, it is noted that a lower visitor investment at CPR exhibits induces a corresponding drop in CPR "failure" probability. Furthermore, the results indicate that visitors who have a lower sensitivity parameter a are less affected by the application of pricing (see bars labeled "charge" that represents the total charge per visitor based on their time investment). This is explained by their tendency to invest a smaller portion of their available time at CPR exhibits, despite gaining higher satisfaction from their visit. Moreover, it can be seen that pricing influences



(a) (b)

Fig. 2. (a) Optimal investment time at CPR and (b) expected prospect-theoretic utility for different loss aversion values and pricing policies.



(a) (b)

Fig. 3. (a) CPR probability "failure" and (b) expected prospect-theoretic utility values, for increasing number of visitors.

visitor time investment more and corresponding expected prospect-theoretic utility less. This observation is a key to improving operation efficiency for cultural heritage space operators.

The line graphs in Fig. 2(a) and (b) illustrate the impact of different pricing mechanisms on visitor investment and expected prospect-theoretic utility, for various loss aversion values k. Both metrics decrease significantly as pricing increases and becomes more aggressive, and this trend is similar for the different loss aversion values k.

Fig. 3(a) demonstrates CPR probability "failure" for different pricing levels as a function of increasing numbers of visitors. We observe that, as expected, CPR "failure" probability increases as the number of visitors increase, whereas it decreases as the price increases. In particular, we observe that for the high charge option, the decrease in "failure" probability when compared with the "no charge" option ranges approximately from 12% to 14%, depending on the number of visitors. Respectively, for the medium pricing option, the corresponding benefits are 5%–7%, with an overall increasing trend as the number of visitors increases.

Fig. 3(b) also reveals that, although visitor expected prospect-theoretic utility drops as the number of museum visitors increases, the influence of charging on visitor expected prospect-theoretic utility remains very small. Taking into account that probability of "failure" is a significant operation parameter that influences both visitor satisfaction and exhibit fragility, it is evident that pricing is a valid and effective tool for reducing this probability. It drives visitors to a more social stable operation point, without excluding them from visiting popular exhibits. As a result, a museum can accommodate a

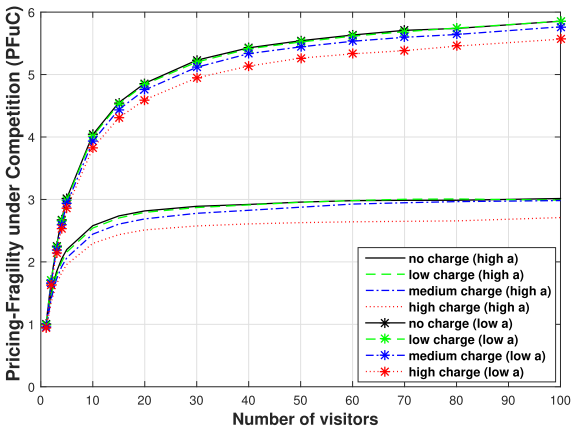


Fig. 4. PFuC as a function of number of visitors.

larger number of visitors at any given time in a satisfactory manner.

In the following, we present pricing-fragility under competition (PFuC), a sociotechnical metric that allows us to further study the effect of competition on CPR exhibits between a single and several self-interested visitors. Specifically, PFuC is defined here as the ratio of the fragility of CPR underpricing when there are several visitors, to the fragility of CPR when there is only one visitor. The fragility of CPR exhibits is expressed by the "failure" probability function, $p(t_T)$ which increases as visitor total investment t_T increases. In particular, the PFuC is given by $PFuC = (p(t_T^*)/p(t_i^*))$. The "failure" probability function, $p(t_T^*)$, is the total investment, t_T^*, at the CPR at the PNE point of N homogeneous visitors, $(N \geq 2)$, under the applied pricing policy. $p(t_i^*)$ is the "failure" probability function of visitor $i, i \in \aleph$ who has the same risk preferences as the group and their optimal investment at the CPR is t_i^* in cases of no pricing.

Fig. 4 depicts that PFuC of CPR exhibits rises as the number of visitors increases, after which depending on sensitivity parameter α, it reaches a peak and then remains stable (upper bounded), regardless of the number of visitors, for all pricing policies. It is also clearly noted that, as pricing increases and becomes more aggressive, the value of the PFuC decreases, which basically quantifies and confirms the impact of pricing on the potential "failure" of the CPR. Furthermore, the results illustrate that the PFuC bound increases when visitors have a smaller sensitivity parameter a, meaning that they become more risk-averse in gains and risk-seeking in losses.

V. Conclusion

In this article, the problem of congestion management in museums is treated from a sociotechnical perspective. Museums are considered as dynamic social environments presenting constraints and interdependencies among the involved subjects and their behaviors thereof. This stimulates the need for the design of computationally efficient and distributed optimization and decision-making approaches regarding visitor touring choices. We have adopted a real-life modeling approach regarding the museum visitor behavior characteristics and reactions, and in particular visitors behavioral risk attitudes with respect to their decisions in resource sharing settings (i.e., different types of museum exhibits to be visited), have been captured and represented by the use of prospect theory.

Motivated by several studies that position pricing as a mechanism to prevent overcrowding in museums, we have analyzed and studied the effect and impact of potential pricing on the decisions and strategies of visitors when acting as prospect-theoretic decision-makers. Based on the obtained results, we have concluded that appropriate pricing policies constitute a valid and efficient measure that drives visitor decisions with respect to their time investment at popular and crowded exhibits, to more effective points from a social welfare point of view. Overall, when appropriate pricing is applied, the adapted visitor decisions and strategies can significantly improve overall museum stability by reducing exhibit "failure" probability, without noticeably affecting the expected visitor experience.

Despite the long history of interest in cultural heritage, congestion management in museums still remains an unsolved issue of significant practical and research interest. Therefore, complementary to pricing, we aim to study framing effects and examine how they can affect visitor choices and decisions in order to further reduce the probability of CPR exhibit "failure."

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